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A comprehensive overview of new designs in the hydraulic, electrical equipments and controllers of mini hydro power plants making it cost effective technology

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ABSTRACT

Implementations of mini hydro schemes with conventional hydraulic, electrical equipment's and controllers have proven very expensive and uneconomical. Many developing countries that are in need of rural electrification have encountered economical problem when setting up these mini hydro schemes. To address this problem, alternative options and new designs of these equipment's have been explored by many researchers around the world. The application of these new designs would reduce the overall cost of mini hydro development and would help in making it a cost effective technology. These new designs will also help developing countries to provide electricity to rural areas or remote regions where interconnection of transmission line from the electrical grid is uneconomical. The new designs can also be an enabling factor in boosting up electricity generation using a renewable energy source. This paper provides survey of all these alternative options and new designs in the controller, hydraulic turbine and generators that have been implemented in different countries of the world.

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1. Introduction

Owing to depletion of fossil fuel and environmental pollutions it produce, many utilities have switched their generation sources to renewable energy. Among the renewable energy sources, mini hydro has gained the highest attraction due to its environment friendly operation. It can be the best economical option for rural electrification in developing countries. However, their implementations have been proven uneconomical due to involving of conventional expensive equipments such as hydraulic turbines, electrical equipment and controllers [1–5]. Since these conventional equipments are designed for large hydro power plant, their usage may not suitable for mini hydro schemes. Conventional hydraulic turbine includes guide vanes which make them more expensive and less efficient for mini hydro applications. To make mini hydro scheme a cost-effective renewable energy option, numerous new designs on hydraulic turbine, electrical equipments and governor controllers have been proposed. By employing these new designs, it could make mini hydro scheme an economical option for rural electrification.

The aim of this paper is to review numerous new designs in different equipment of mini hydro power plant which has been found a cost effective option. Several recommendations for making these mini-hydro schemes a cost-effective option for rural electrifications in developing countries are also presented. It is expected that this paper will assist industries of developing countries in the selection of the most economical mini hydro scheme for a specific site.

2. Mini hydro renewable energy potential-an overview

Hydro power plants are the most widely used renewable energy source worldwide. It provides 19% of the world's electricity. The hydropower potential on large scale has been exploited in almost every part of the world. However, its potential at the small scale remains unexploited. The mini hydro energy source is available in almost every country of the world. Fig. 1 shows a brief account of current potential in different continent of the world [1].

It can be seen from Fig. 1 that Asia, Africa and South America still have a large potential for mini hydro which has not been exploited yet [1]. The proportion of mini hydro source with other renewable energy sources till end of year 2008 is shown in Fig. 2 [6].

It can be seen from Fig. 2 that among the renewable energy sources, large hydropower, biomass heating, solar heating system, wind and mini hydro have significant proportions in supplying electricity demands. It is reported that 40 GW of electrical energy demand is supplied by mini hydro power plants and has a global potential of more than 100 GW [1]. The largest installed capacity of mini hydro around the world is in Asia followed by Europe. Fig. 3 shows the installed capacity of mini hydro in top five countries up to 2009.

Fig. 3 shows that China has the highest installed capacity of 59% followed by Japan having 11% capacity of mini hydro. USA, Italy and Brazil have mini hydro capacity of 8%, 3% and 3% respectively [7]. China produces 15 GW of electricity from mini hydro power plants and planned to produce further 75 GW of mini hydro by 2020 [1,7]. UK generated 100 MW from 120 sites [1]. Europe has also intensive planning to produce more mini hydro power plants. The forecasted production of mini hydro in Europe for 2015 is shown in Fig. 4.

It can be observed that the Czech Republic, Romania, Poland, Turkey and Bulgaria has the target of more than 300 MW by 2015 [8]. Malaysia gets 18,500 MW of electricity from hydro power plants including large, small and mini hydro power plants. Recently from a reconnaissance study, 28.9 MW potential of micro hydro power plant is identified in west Malaysia [9] and 50 kW micro-hydro plant is developed in Malaysia with head of 10 m and water flow of 1 m^3 per second using an induction generator [10]. Canada has over 1600 identified potential sites that may be suitable for 100 kW micro-hydropower [5]. Sri Lanka has a mini hydro potential of 97.4 MW [11]. Bangladesh has

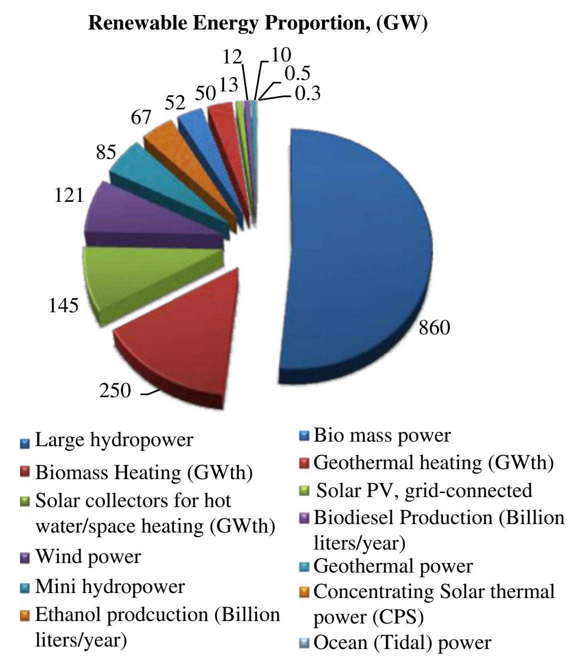

Fig. 2. Global proportion of renewable energy sources [6].

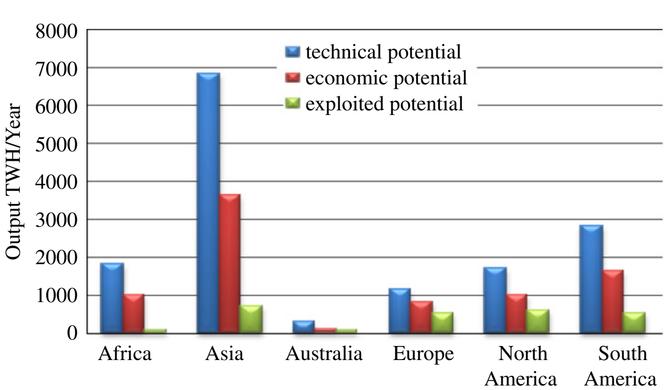

Fig. 1. Exploited hydro potential by continent [1].

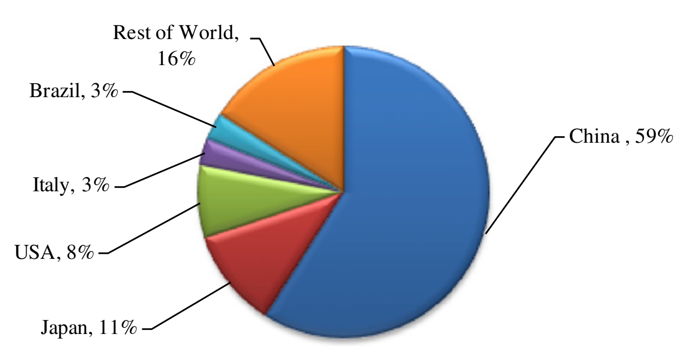

Fig. 3. World top five countries having largest installed mini hydro capacity [7].

installed a 10 kW micro hydro plant through private efforts which illuminated 140 houses of that area including a Buddhist temple [12].

Mini hydro technology is a mature and reliable technology, with easy operation and having a life cycle more than 50 years. The mini hydro power is more efficient than other sources of renewable energy like wind or solar. Solar cells convert about 10% to 12% of light energy directly to electric energy whereas micro hydro units have efficiency between 60% to 90% range [13]. Mini hydro plant resulted in reductions of around 950, 12 and 5 tons of CO_2, SOx and NOx respectively when compared with equivalent thermal power plant [14]. When compared with diesel plant, a 2.5 kWh of energy through micro-hydro saves 1 litre of diesel and 2.5 kg of GHG emission. 25% replacement of diesel generation through micro-hydro schemes will result in reduction of 0.3 MT of GHG emissions annually [5].

Despite of having all these advantages, a large potential of mini hydro resources is not fully exploited. The major barriers in making mini hydro a cost effective technology are the huge costs of civil construction, electromechanical equipment and the long delay in approval processes [5]. Paish [1] has pointed out that the barriers in development of mini hydro in Europe are mainly consists of institutional and environmental issues in getting approval for implementation of new schemes which has left the industry in stand-still position. Kaldellis [15] has pointed out that administrative bureaucracy is one of the main obstacles in deceleration of these schemes in Greece. As a result it takes almost three years to get final license to start work. Furthermore, the lack of integrated national water management plan in Greece is another serious obstacle for the mini hydro schemes development [15].

3. Current developments in mini hydro schemes

3.1. Basics of mini hydro working principle

The mini hydro power plant mainly consists of a small reservoir or irrigation canal, governor, turbine and generator. The schematic diagram of mini hydro power plant is shown in Fig. 5.

The water is passed from reservoir to turbine through penstock. When water strikes at the blades of the turbine, it converts hydraulic energy into mechanical energy. The hydraulic turbine transfer function is given by Eq. (1).

$$\frac{\Delta P_m}{\Delta G} = \frac{1 - T_w S}{1 + 0.5 T_w S} \tag{1}$$

where, ΔP_m shows turbine mechanical output power in per unit,
ΔG shows gate opening of turbine in per unit and,
T_w shows the water starting time of the turbine.

Water flow in the turbine is controlled through governor. Main function of governor is to control generator speed so that its frequency remains constant. Gate position of turbine is controlled through servomotor, which adjusts water flow to produce power according to load connected. The transfer function for relay valve

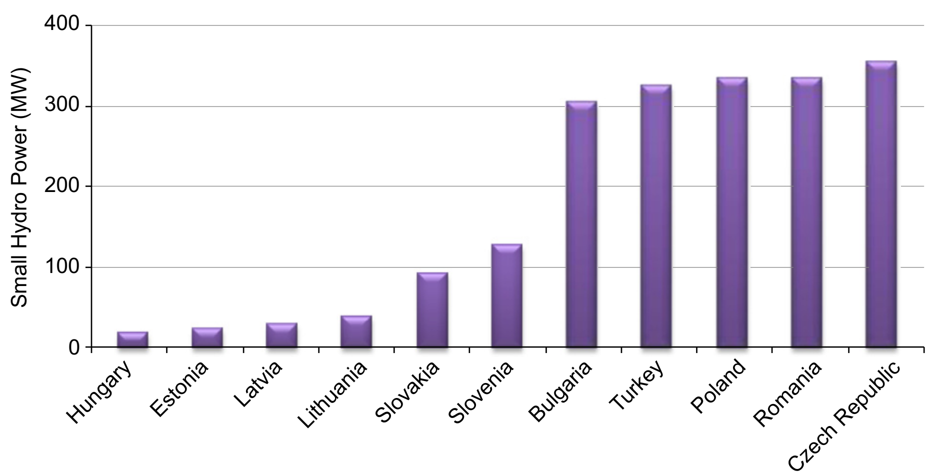

Fig. 4. Forecasted mini hydro power in different countries of Europe in 2015 [8].

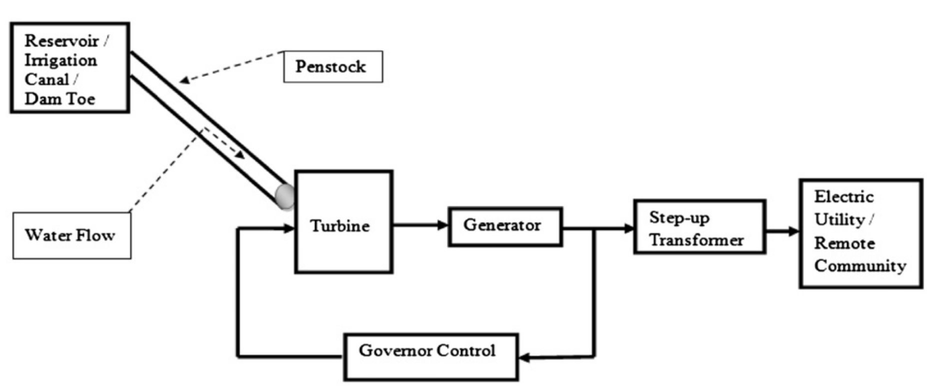

Fig. 5. Schematic diagram of a mini hydro power plant.

and gate servomotor is given by Eq. (2).

$$\frac{g}{b} = \frac{K_s}{s(1+sT_P)} \tag{2}$$

where, K_S is the servo gain and T_P is the pilot valve/servomotor time constants.

The turbine is coupled with generator which converts mechanical energy into electrical energy. The generated power through mini hydro is given by Eq. (3) which is then stepped-up through a transformer and supplied to grid or to an isolated community.

$$P = \eta \times \rho \times g \times Q \times H \tag{3}$$

where, P is mechanical power produced,

η is hydraulic turbine efficiency,
ρ is water density,
g is acceleration due to gravity,
Q is water flow rate and
H is water head.

At present, mini hydro schemes employ conventional equipments which are expensive and uneconomical for implementation. In order to make mini hydro schemes a cost effective technology different new designs have been proposed in almost every component of mini hydro power plant. The new designs involve penstock, hydraulic turbines, generators and governor controller. By implementing the new designs, mini hydro can be a cost-effective option for rural electrification programs.

3.2. New designs in hydraulic turbine shape

The choice of turbine for hydro power plant depends upon the head and discharge from the available site. Table 1 shows different type of turbines with their operating heads and specific speeds. Commonly, there are two types of hydraulic turbines, Impulse turbine and Reaction turbine. Impulse turbine operates at a high head and has two types, Pelton Wheel and Cross flow turbine. The Pelton wheel turbine is suitable for low specific speed and high head (> 240 m), whereas the Cross flow turbine is suitable below the range of Pelton Wheel turbine (180 m) [16].

The Turgo turbine is also classified as a type of Impulse turbine. It is similar to the Pelton Wheel and suitable for Pico Hydro Systems and offers high efficiency for a broad range of site conditions. Turgo turbines are supposed to be reliable, robust and able to operate efficiently over a range of flow rates. Turgo turbine can handle significantly higher water flow rates, allowing for efficient operation in lower head ranges. Under the best conditions, Turgo turbine efficiency is observed to be over 80% [17]. Moreover, the performance of a single-jet Turgo turbine is investigated at low heads of 3.5 m–1 m range. This design improves the turbine performance up to 91% efficiency at 3.5 m head and 87% at 1 m head [18]. Williamson et al. [19] performed quantitative and qualitative analysis on 13 different types of turbine to find a suitable one for low-head Pico hydro systems. The paper recommended that propeller turbine variant or single-jet Turgo turbine is a viable option for these schemes. Reaction turbine operates at a medium or low head. There are three types of reaction turbine, namely Francis, Kaplan and Propeller turbine. Francis turbine is suitable for medium specific speed and medium head (> 55 m < 240 m), while Kaplan and propeller turbine are suitable for high specific speeds and low heads (< 30 m). Meanwhile, Bulb turbine is also developed in Europe for large rivers with high flows. The design in rotor blades of mini hydro Bulb turbine is discussed in Ref. [20], and its inlet guide vane system is validated experimentally in Ref. [21]. This is more economic choice than Kaplan for 3 m–23 m range. S-type turbine which is the modified form of small Kaplan turbine with horizontal inlet is suitable at heads between 1 m–15 m [16].

Research work has been carried out on alternative option and new designs in hydraulic turbines making it more efficient for mini hydro schemes. Anagnostopoulos and Papantonis [22] presented optimum sizing of mini hydro power plant by using two Francis turbines of different sizes. Since, a lot of water is wasted due to variation in flow rate of stream water, which can be utilized efficiently by employing two turbines of different sizes or types. Depending upon the flow, either both or single turbine can run to exploit maximum flow which resulted in 25% more power production than with a single turbine. The size ratio for both turbines producing optimum results is found in 0.4–0.5 range. Magureanu et al. [23] provided optimal solution for the successful operation of the Francis turbine in mini hydro power plants. Usually, a turbine provides maximum efficiency if water flow is more than or equal to 80%. However, in practice, the water flow for mini hydro plants varies dramatically. Francis turbine operates satisfactorily at least for more than 50% water flow. Water flow below 40% causes vibration or mechanical shocks which may lead to instability. The only way to get maximum efficiency from this turbine is to run the turbine at variable speed. Turbine runs at lower speed on smaller discharge and at higher speeds at larger discharge. The neural network model of an axial-flow propeller turbine operating at variable speed for obtaining high efficiency is also discussed in Ref. [24].

Due to small capacity of mini hydro plants, conventional hydraulics turbines proved costly and fail to provide satisfactory efficiency making mini hydro schemes uneconomical [2,4]. To make best use of these schemes within economical range, various new designs in hydraulic turbines have been applied. The simplified designs of Cross flow and Pelton Wheel turbine are developed and tested in Nepal from the mid-1970s and these simplified designs are also adopted in Sri Lanka, Peru and Indonesia [1]. Bangladesh produces his indigenous 10 kW micro hydro power plant through wooden turbine and earthen dam illuminating 40 families which got very much attention by electronic media [12].

Williams and Simpson [25] suggested new designs in hydro turbine and penstock for improvement in efficiency. The penstocks with large diameter are cost-effective for Pico hydro plants. The number of buckets can be reduced from 18 to 16 and painting the buckets for good surface finish provides 72% efficiency of 1 kW turbine. Guide vanes can be removed to further increase the efficiency. Márquez et al. [26] provided new design of high speed propeller turbine removing all mechanical adjustments and implementing a power electronic system for grid connection.

Table 1
Operating characteristics of different turbines [1,16].

Turbine type		Operating head	Specific speed
Impulse turbine	Pelton wheel turbine	High head < 240 m	Low specific speed
	Cross flow turbine	Lower than Pelton wheel (180 m)	Low specific speed
Reaction turbine	Francis turbine	Medium head (> 55 m < 240)	Medium specific speed
	Kaplan turbine	Low head (< 30 m)	High specific speed
	Propeller turbine	Low head (< 30 m)	High specific speed

Alexander and Giddens [3] performed detailed work through the University of Canterbury project on new cost-effective designs of hydraulic turbine and penstock for micro-hydro plants. The scheme was aimed for low heads sites where Pelton wheel could not run optimally and economically. The purpose of this project was to design low-cost, well designed turbine for 0.2–20 kW range. The main objective of these designs is that these turbines resist debris blockage and easily built by third world countries in their local workshops. It was expected that the proposed scheme will result in cost reduction of 1/3 in turbine, 1/3 in penstock and 1/3 in electrical equipments [3]. The main problem in these turbine designs was to predict the cost-effective penstock for optimum discharge through a specific diameter from available piping. The main aim behind this penstock optimization was to reduce the overall capital cost per kilowatt. The penstock is one of the expensive equipments for micro hydro schemes because the penstock cost is around 1/3 of the total costs of the micro-hydro scheme. It was observed that site slope of particular plants plays a vital role in the cost of the penstock. The slope of penstock is the main consideration in reducing or increasing its cost. The slope of penstock is the ratio of gross head to length of penstock ($S = Hg/L$). For a specific site, a reduction in slope means increase in the length of penstock which results in an increase in price. The comparison proved that the smaller penstock is more economical. As the optimum discharge slightly depends on slope and has been determined at 1 in 8 slopes and optimum choice for steeper slope was 1 in 4 having 0.167 discharge. The commercially available uPVC is proved the most economic material for penstock [27]. Ranjitkar et al. recommended high density polyethylene (HDPE) pipe for penstock that have been utilized for micro-hydro schemes all around the world. HDPE has the lowest cost, easy transportation and installation on hilly regions. In some cases HDPE penstock cost proved half of the mild steel penstock cost [5].

The design in turbine essentially depends upon specific speeds and the purpose is to find suitable turbines rather than Pelton wheel. Hence, the specific speeds are chosen between 36 (high heads) to 600 (low heads) range. Depending upon the specific speed, the turbine shape remained same. However, size was scaled for adjusting with penstock at low heads and low discharges in water flow. For this purpose, a modular concept was applied on five different turbine designs each of which has a different specific speed and shape. The guide vanes were eliminated in new designs. The runners and casings of turbine designed used mild steel plate for simple fabrication. The designs of axial flow propeller turbine have been provided for economic turbine solutions. These turbines are suitable for low head micro hydro systems making low head power schemes, an economical technology for rural electrification. The axial flow propeller turbine is designed in new shape at four different specific speeds operating at heads of 2–40 m range [4]. The mixed-flow and radial-flow turbines are developed to cover head of 2 to 50 m range. The turbine blades are made up of a flat plate for ease of manufacture. The radial-flow design is implemented to operate at heads below than the range for multiple-jet Pelton wheels. The propeller turbine with radial flow has resulted in obtaining more than 70% turbine efficiency. A mixed flow turbine which combines both axial and radial flow has larger radius at the exit than at the inlet. The water flow in mixed flow turbine tends to exit in an axial direction rather than in a radial direction [2].

For dealing with micro hydro schemes operating at the heads of 1.5–2 m, Singh and Nestmann [28] has applied free vortex theory to optimize the efficiency of propeller by applying the modification in its tip angle. For this purpose, the optimization of four propeller runner models operating at low heads giving power of 1.5–3 kW has provided. This provides peak efficiencies of 68–74% on an experimental system. The free vortex law is based on the law of conservation of momentum. For this, the irrotational flow must be satisfied with an axial velocity. It was concluded that the runner performance was very sensitive to changes in exit tip angle. By employing two levels of modification, a 15–30% increase in discharge and 12–45% increase in shaft power is observed. The efficiency of turbine was increased from 55–74% by employing modification at the runner inlet tip. The paper recommended not to use guide vanes in the turbine design [28]. Singh and Nestmann [29] presented another study on the theoretical model of runner and investigated the effects of blade number and height of blade on the axial flow propeller turbine and experimentally applied on three runners. The results have shown the influence of changing the number of blades is more dominating than the influence of change in blade height. Hence, number of blades should be carefully selected. It was recommended that the number of blade should not be increased in the turbine. Table 2 shows the summary of new designs in hydraulic turbine shape.

3.3. Pump as turbine (PAT): alternative option to turbines

The initial cost of mini/micro hydro plants largely depends upon the cost of equipments. One way to reduce this cost of equipments is to use Centrifugal Pump as a Turbine (PAT). PAT can be considered as a cost-effective alternative and viable option for mini/micro hydro power generation especially in rural hilly

Table 2
Summary of new changes proposed in turbine shape.

Main theme for new design	Change in designs	Advantages
Two turbine of different size and type to generate more power [22].	Two Francis turbines of different size are employed.	25% energy has been increased. This technique provides cost-effectiveness in total economy of plant
Variable speed operation of mini-hydro power plants to improve efficiency [23,24].	Model considered axial flow propeller turbine with four adjustable guide vanes.	Turbine efficiency been improved by changing guide vanes position.
Removing mechanical adjustments in hydro turbine and changing the penstock length to improve the efficiency [25,26].	Number of buckets was reduced from 18 to 16. Turbine employed radial guide vane configuration.	Penstocks with large diameter are cost-effective for Pico hydro plants. Painting the buckets for good surface finish provides 72% efficiency.
Optimum size of penstock is determined. New designs in axial radial and mixed flow propeller turbine were made in such a way that they can be easily built by third world countries in their local workshops [2–4,27].	Guide vanes were eliminated. Turbine runners and blades employed mild steel plate and flat plate for simple fabrication.	Maximum cost-effectiveness. uPVC is proved as most economical material for penstock. Turbine efficiency is achieved up to 70%.
Application of free vortex theory to optimize propeller efficiency by applying modification in its tip angle [28] and investigates effects of blade number and blade height on it [29].	Tip angle of turbine blades was changed. Number of blade and blade height was changed.	Peak efficiencies of 68–74% are obtained.

areas and in agricultural land areas. PAT being mass produced all over the world is a standard product available in variety of sizes of different head and flow rates. These are cheaper and easily available in the market. Their repair and maintenance can be easily carried out by local technicians. The PAT cost is 50% less than the cost of conventional turbine. PATs are available in wide variety of 1.7 kW and 160 kW range [5]. PAT is basically a pump which can operate in a turbine mode if the direction of flow is reversed. When it is operated in the turbine mode its efficiency is higher than in the pump mode operation. With suitable conditions, PAT can cover the range of multi-jet turbines, cross-flow turbines and small Francis turbines. Thode and Azbill [30] has used standard pumps for electrical power generation operated in the reverse mode. It is observed that axial, radial and mixed centrifugal pumps operating in reverse mode can also operate as a turbine. Furthermore, Williams [31] presented the PAT implementation in different micro hydro plants in which three examples of PAT in different countries are discussed. Typical power capacities of plants were 3.5 kW, 4 kW and 4.5 kW with PAT installed in Barnacre, North–West England, Yorkshire Dales of North England and West Java, Indonesia respectively. PAT for large power capacities ranging from 20–200 kW have been installed at Peru and Guatemala replacing the small Francis turbine [31]. Currently Lao People's Democratic Republic country situated in South East Asia [32] has implemented PAT for Pico-hydro plant development in a village in Xiagnabouli province. A 2 kW PAT scheme is proposed for a village consisting of 86 households in Xiagnabouli province. Implementation of PAT reduces the cost 53% as compared with cross-flow turbine [32].

Despite of having many advantages over conventional turbine, PAT has one drawback. The prediction of turbine characteristics of the centrifugal pump is very difficult. PAT selection for a specific mini hydro site is a major problem. Ramos and Borga [33] compared mathematically the performance characteristics of PAT for determining maximum efficiency of 80%. Joshi et al. [34] provided another simple method for PAT selection suitable for a case study having 25 kW power at 5 m head. The case study considered experimental data of three pumps and characteristics at constant head and constant speed were derived to assist its operation. Performance of the pump at constant head showed many similarities with the performance of the axial flow turbine. To investigate further the turbine characteristics of pump, Derakhshan and Nourbakhsh [35] presented a detailed theoretical model of four centrifugal pumps tested as turbines for the calculation of expected efficiency.

Several researchers have provided different methods regarding prediction of turbine characteristics of pump. However, failing in proper understanding of flow physics in these machines has rendered their optimum prediction. Computational fluid dynamics (CFD) is suitable technique for predicting the pump performance as turbine by using geometric data with fluid properties. Rawal and Kshirsagar [36] and Derakhshan and Nourbakhsh [37] applied a CFD simulation on PAT and from simulation and experimental results had shown the feasibility of centrifugal pump operation as turbine with satisfactory efficiency. However, turbine characteristics of pump still cannot be generalized and needs more intensive research and modeling.

Nautiyal et al. [38] presented the experimental study of a centrifugal pump operating in both pump mode and turbine mode having specific speed 18 (m, m^3/s). As compared to other methods, the proposed relation has a low deviation. However, some uncertainties still remain in the prediction of turbine mode characteristics. Nautiyal and Kumar [39] discussed all the analytical analysis, experimental and computational fluid dynamics studies regarding the prediction of turbine characteristics of centrifugal pump. It concludes that despite adapting lot of methods for determining the optimum behavior of pumps from analytical analysis, experimental as well as computational studies optimum results still have not been found. The reason for this is that manufacturers of pumps do not provide their characteristics curves and it is very essential to know about the characteristics of pumps for successful operation of pumps as a turbine. Hence, there is a need of intensive research in this area for getting maximum efficiency of PAT. Summary of PAT including its advantages and disadvantages are shown in Table 3.

4. Induction generator as a source of power generation

A great deal of research has been carried out regarding the application of the induction generator as an alternative source for power generation over the synchronous generator in mini/micro hydro schemes for making these schemes cost effective. The induction generators have reduced cost per unit of electricity as compared to synchronous generators. Besides, induction generators are more robust and have easy starts and control mechanisms, self-protection against faults. It has the ability for generating power at changing speeds and can be used in an off-grid or interconnected mode with synchronous generator for load sharing. It can also be operated as generator when its stator winding is connected with capacitor and rotor is driven by prime mover. In that case the magnetizing lagging reactive power is provided by the capacitor. This capacitor establishes the air-gap flux. This configuration enables the induction machine to work as a self-excited induction generator. Induction generators excited with capacitor are emerging as a suitable candidate for renewable energy power generation operating in stand-alone mode.

Despite all these advantages, induction generators have encountered problem in maintaining the frequency and voltage within its range. Induction generators very often equipped with Automatic Voltage Regulator (AVR) to control voltage. However, induction generators with AVR are more expensive and will outweigh the advantage of induction generators for use in micro hydro systems. Hence, induction generator controller (IGC) can be employed for the same purpose as electronic load controllers (ELC). A new simple cost effective technique for controlling the induction generators with IGC operating in isolated micro hydro power system is discussed in Ref. [40]. When a lagging power factor load is applied on a generator, voltage of the generator decreases, at that position IGC takes action by reducing the load on ballast load for maintaining frequency and voltage. The ballast/dump load is resistive load connected with the power plant which will dissipate any extra power in case of load variation. Currently

Table 3
PAT advantages and disadvantages over conventional turbine.

Advantages of PAT	Disadvantages of PAT
PAT can cover the range of multi-jet turbines, cross-flow turbines and small Francis turbines.	Predictions of turbine characteristics of centrifugal pump are very difficult.
Cost of PAT is comparatively 50% less than conventional turbine because of being mass produced all over the world and are standard product available in variety of sizes of different head and flow rates.	PAT selection for a specific mini hydro site is a major problem.

more than hundred IGC's has been installed in different countries of the world (Africa, Asia and Europe) ranging from 1 kW to 30 kW. IGC's are also built in England, Indonesia, Nepal, Philippines and Sri Lanka. By using this technique the need of separate AVR source for compensating inductive loads is eliminated [40].

Another technique for frequency and voltage control in induction generator operating in isolated mode is discussed in Ref. [41]. The technique considered voltage source inverter (VSI) with dump load. The voltage source inverter consists of three-phase PWM inverter using six transistors. This technique has advantage that it maintains the frequency even when dynamic loads like the induction motor is connected. The control of autonomous induction generator over a varying speed of turbines is presented in Ref. [42]. The control technique employed a rotor flux oriented vector control method.

4.1. Single-phase operation of three-phase induction generators: new trends

Micro hydro schemes are mostly adapted for providing electricity to rural communities located far away from the grid and normally consist of a single-phase resistive load. Single-phase induction generator are expensive than three-phase induction generator according to cost of per kilowatt (kW) [37]. Three-phase induction generators can supply single-phase loads by converting their three-phase power into single-phase power with suitable techniques. Many researchers have proposed several techniques for single-phase operation of three-phase induction generators. Ion et al. [43] provide conversion of single-phase from a three-phase by adopting voltage source inverter and dump load combination for regulating the frequency and voltage for successful operation. Ekanayake [44] provided C-2C connection for the conversion of three-phase to single-phase for cost effective results. The scheme used IGC operated through IGBT electronic switch for maintaining the induction generator's voltage and frequency during any change in load. Rather than using separate different values of excitation capacitances connected with stator phases for balancing stator currents, Kumaresan [45] has replaced this with a three-phase capacitor bank of required magnitude. Induction generator supplies single-phase and three-phase loads of different nature (resistive and inductive loads as well as AC and DC separated and combined).

The techniques applied for the conversion of three-phase to single-phase when operating in connection with single-phase power grid are known as smith connections. These connections were introduced by Smith in 1991for the successful operation of three-phase induction motors to a single-phase motor. Chan and Loi Lei [46] applied this technique for the operation of three-phase induction generator operating on single-phase power grid. Smith connection is a method in which proper selection of terminal capacitances enables three-phase induction generator to operate successfully with balance phase currents and voltages. The connection is computed through a symmetrical components method at different speeds of the rotor. Chan and Lai [47] applied special type of smith connection named Mode C for successful single-phase operation of a three-phase induction generator connected with single-phase power grid. The Mode C connection uses two capacitances and transformer for phase balancing. This method deals with three-phase induction generator connected in delta connection.

A new ELC controller for three-phase induction generators with delta connection suitable for Pico hydro schemes operating off-grid is proposed by Singh et al. [48]. The controller consists of an uncontrolled rectifier, capacitor, chopper and dump load. The proposed ELC offered advantage of being simple, cheaper and reliable over other existing ELC controller because it requires less complicated components. ELC is designed for both three-phase and single-phase loads. With little modification, induction generator can be operated as three-phase as well as single-phase depending upon the application. Three-phase induction generators are available with both delta and star connections requiring separate techniques for conversion of three-phase into single-phase operation. Mahato et al. [49] proposed a technique for single-phase operation of three-phase star connected induction generators. The technique was applied for determining transient behavior, by using three capacitors connected in series for conversion of single-phase.

Jain et al. [50] designed a generalized and experimental model for three-phase self excited induction generator delta connected when subjected to unbalanced faults. It concluded that during imbalance, difference in the stator current is more significant

Table 4
Summary of new techniques in Induction generator.

Main concept	Advantages
Problem of frequency and voltage stability in induction generator can be reduced by employing IGC [40] and voltage source inverter with dump load arrangement [41].	This technique eliminates requirement of separate AVR for compensating inductive loads. This technique maintains frequency even when the dynamic load like induction motor is connected.
Rotor flux oriented vector control method is applied on induction generator for varying speed of turbines [42].	Simulation results provide good agreement with experimental results.
Three-phase induction generator can be converted to single-phase by adopting voltage source inverter with dump load combination [43] and C-2C connection [44].	Three-phase is comparatively cheaper than single-phase Three-phase operation of single-phase provides good voltage and frequency regulation. This technique provides cost effective results.
Three-phase capacitor bank is applied rather than using separate capacitance values [45].	Voltage regulation is improved.
Smith connection [46] and Mode C connection can successfully convert three-phase induction generator into single-phase [47].	These connections enable three-phase induction generator to operate successfully.
Induction generator can operate as three-phase or single-phase depending upon the application by using ELC controller [48].	Proposed ELC offered advantage of being simple, cheaper and reliable over other existing ELC controller.
Three-phase star connected Induction generator can be converted in to single-phase by using three capacitors connected in series technique [49].	Proposed technique has shown improvements in voltage regulation.
Generalized and experimental model for three-phase delta connected induction generator subjected to unbalanced faults [50], and its steady state performance when supplying three-phase unbalanced/ single-phase loads is tested [51].	Faults results in the de-excitation and collapse of voltage in the system. This technique provides powerful tool for design of mini hydro plant because these plant mostly supplies single-phase and unbalanced loads.
Induction generators with dump load combination fail when load is more than total generation. This problem can be overcome by replacing dump load with Storage device like battery [52].	This technique provides better results in frequency and voltage control even when the load is higher than the generation.

than stator voltages, and faults results in de-excitation and voltage collapse in the system. Murthy et al. [51] presented a new generalized method implemented on experimental set-up for determining the steady state performance of three-phase induction generator supplying three-phase unbalanced loads/ single-phase loads. As the mini hydro mostly supplies single-phase and unbalanced loads, this technique will prove a powerful tool for such system design. When induction generators are employed in micro hydro power plants with dump load and load is more than the total generation, then dump load technique fails to provide satisfactory control of voltage. To deal with this problem Marinescu and Ion [52] proposed storage device like battery rather than dump load for providing the stability to stand-alone micro hydro plant. The technique proved that storage device provides better results in frequency and voltage control even when the load is higher than the generation. During this, battery discharges and supplies stored energy to cope with the increased demand. Table 4 shows the summary of new techniques proposed in the induction generator.

4.2. Six-phase induction generator replacing three-phase induction generator: latest trends

Research for more than two decades has shown the technical and economical feasibility of using more than three-phase in AC machines especially in induction motors. The general application includes marine ships, electric vehicles and nuclear power plant. Though research is still in the early stages, yet interesting findings have been observed showing more advantages compared to the three-phase induction machines. The advantages of six-phase induction machines over conventional three-phase winding includes amplitude reduction and increased frequency in torque pulsations, harmonics currents of rotor and current per phase are reduced [53]. Literature review on multi-phase induction generators shows that it is almost unavailable since only three studies have been reported in the literature before 2005 as reported by Singh et al. [53]. First, multi-phase induction generator technique was based on a brushless dual-stator winding, one winding of the stator provides electromechanical power conversion, while the other is used for excitation to give three-phase power output [54]. The remaining two other studies discussed multi-phase induction generator having double-stator winding with an extended rotor common to both stators [55,56]. However, output was three-phase in all these schemes. So far the implementation of multi-phase induction generator in renewable energy such as mini hydro and wind is still unreported. First work on a six-phase induction generator implemented in mini hydro was reported in 2005 by Singh et al. [53].

A six-pole six-phase connection was obtained by splitting the phase belt of conventional three-phases into two groups. Split phase induction machine are special type of multi-phase induction motors that have two similar three-phase stator windings. Six-phases of stator are divided into 2-Y connected sets of three-phases. Magnetic axis of these three-phase set are displaced from one another by a 30° electrical. The neutral point of these three-phase set are isolated from each other to avoid the propagation of fault through one set to other. These winding shares the same magnetic circuit. This six-phase technique enables induction generator, self excited and self regulated, operate successfully with a bank of shunt capacitor which is connected either to one three-phase winding or both three-phase windings. Voltage regulation of six-phase induction generator is improved by connecting series capacitor which provides the additional required reactive power. Mathematical modeling of six-phase self-excited induction generator was developed in d–q reference frame through nodal admittance method solved by graph theory in matrix form. The equation of matrix developed through nodal admittance method was solved by Newton Raphson method for determining steady-state performance of the Six-Phase Self Excited Induction Generator (SPSEIG) [57] and by a genetic algorithm (GA) method for determining the frequency and magnetizing reactance [58]. In the analytical model, for 2 three-phase winding sets, effects of dynamic cross saturation common mutual leakage inductance have been included. The model has advantages that the core loss component and mutual coupling effects can be easily eliminated or included [59].

In order to make the six-phase induction generator self excited, a suitable value of the capacitor is required. An optimal method for obtaining these values for series and shunt capacitance for successful operation of SPSEIG is calculated in Refs. [60–62]. The schematic diagram of the proposed six-phase SEIG is shown in Fig. 6. The Fmincon optimizer is applied for determining the unknown frequency and magnetizing reactance per phase. The Fmincon optimizer is a built in function in optimization tool box of Matlab. It is applied to get a constrained minimum of a scalar function having many variables beginning at an initial estimate. It is commonly known as constrained nonlinear optimization. This technique enable the generator to successfully operate as self-excited and has another advantage that it can supply two independent three-phase loads [63]. Six-phase induction generator has another advantage that two three-phase winding's output can be combined and supplied to a single three-phase load. This is done by employing a transformer having six-phase to three-phase windings. This technique has the advantage that in case of failure in any of three-phase winding, the system will not be shut down but continues to supply load from the remaining

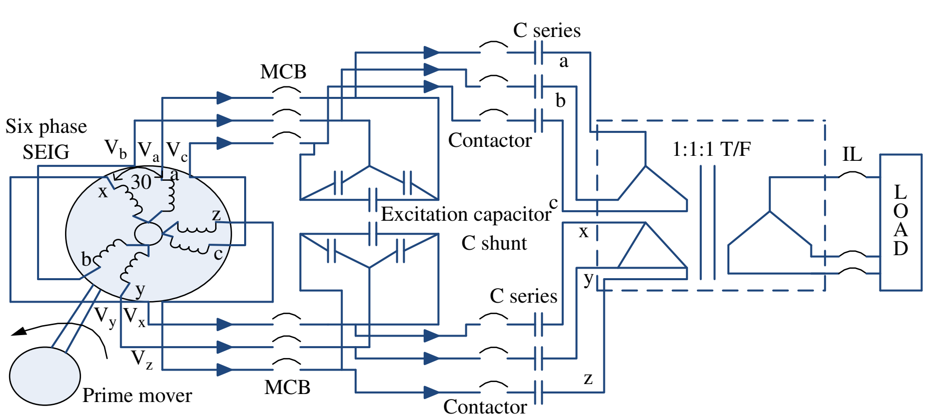

Fig. 6. Schematic diagram of induction generator system employing a SPSEIG [61].

healthy winding. This offers an improved reliability in comparison to three-phase induction generator [58].

The experimental feasibility of SPSEIG in the mini hydro power scheme was verified on no load as well as at resistive loads [64,65]. From experiments, it is concluded that in the six-phase induction generator, variation in terminal voltage, current and sensitivity to speed during self-excitation is lower than with the three-phase induction generators. Power conversion efficiency and overall efficiency of six-phase induction generator is more than the three-phase induction generator. Its performance analysis with different capacitor excitation topologies like simple shunt, short shunt and long shunt is discussed in Refs. [66,67]. The generator voltage when observed with a simple shunt excitation resulted in voltage collapse but it was able to sustain when either the short shunt or long shunt excitation connection was applied. The series compensation is known as short shunt. Six-phase induction generator has the additional advantage that it can supply two separate three-phase loads simultaneously. This configuration has some drawbacks that voltage regulation is poor. In order to regulate voltage, additional schemes are applied which consists of a combination of short and long shunts. Experimental results have shown that the short shunt is suitable for voltage regulation while simple shunt is suitable for efficiency. The results are tested both on resistive and inductive as well as combination of both [66,67].

4.3. Six-phase synchronous generator

Practical implementation of six-phase synchronous generator was started in 1970s and 1980s. However, so far all proposed applications were strictly limited to Uninterruptible Power Supply (UPS) systems. Nowadays, the application of six-phase generators has begun again for renewable energy applications. However, in the past none has adapted six-phase synchronous generator in mini hydro plants to show its economical viability. Singh [68] experimentally investigated the steady state behavior of six-phase synchronous generator. The aim of the study was to find additional advantages possessed by six-phase synchronous generator over conventional three-phase generator. The three-phase synchronous generator was formed the six-phase by adapting a phase belt splitting. The schematic diagram of the proposed six-phase synchronous generator is shown in Fig. 7. It should be noted that 30° electrical displacement is of great interest because it allows re-combination of three-phase power in step-up transformer bank.

Experiments were carried out on constant voltage as well as on constant frequency/speed operation. Six-phase has an advantage that it can supply two three-phase loads separately. Another advantage of using this scheme is that by employing a transformer having six-phase to three-phase windings, output of two three-phase winding can be supplied to a single three phase loads. The use of transformer has advantage that in case of failure in any of three-phase winding set, system will not lead to shut down but load continued to be supplied through remaining healthy winding thus improving system reliability. A comparative study concludes that six-phase generator deliver more power, better speed and voltage regulation than three-phase synchronous generator [68].

5. Hydro-governor controllers

Mini hydro power plants (MHPP) due to their complex nature and nonlinear behavior of hydraulic turbine encountered frequency and voltage variation in the system. Different control techniques are needed for maintaining voltage and frequency within the range. Voltage can be maintained by varying the excitation and frequency can be controlled by making generation equal to load through governor control. In the past, mechanical hydraulic governor were applied for this purpose which is now replaced by electro hydraulic PI/PID governor. Fundamental mathematical models of all these governors and turbine suitable for hydro electric power plant are discussed in Ref. [69]. The paper described in depth concerning linear, non linear, elastic, non elastic surge tank effect, traveling wave effects on hydraulic turbines and provides their models for simulation studies [69]. The basic four models of speed governing system suitable for steam and hydro turbine with their basic models for power system stability studies have been discussed in Ref. [70].

5.1. Conventional control methods

Different governing control techniques for frequency stabilization are discussed in Ref. [71] covering PID controller to intelligent control techniques. PID controllers have better response in dealing governor control because it provides three functions to control the system. The proportional, integral and derivative function provide reduction in rise time, zero steady state error and reduced oscillation enabling system to respond quickly during load disturbances. Salhi et al. [71] applied PI controller technique on Micro Hydro Power Plant prototype for load frequency control. PI controller ensures good results canceling the steady error of frequency [71]. PID controllers best deals with linear models and are suitable for second order systems and fail to provide satisfactory control to non-linear systems having severe problem of integrator wind-up [72]. Atherton and Majhi [73] discussed the limitations of classical PID controllers. The paper provides an alternate solution for improvement in performance by employing a combination of PI and PD and finally comparison is provided between this with other techniques designed by various authors.

Poulin and Pomerleau [74] proposed a novel method by using constant M circles in Nicholas chart for obtaining PI/PID

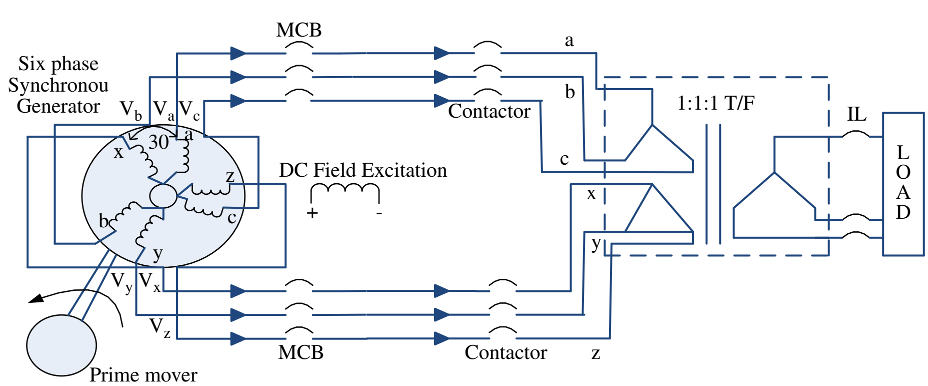

Fig. 7. Schematic diagram of six-phase synchronous generator [68].

controllers parameters. The concept behind this technique is that a maximum overshoot of the system response should remain in a pre-determined value followed by a step change in original input. The proposed technique is known as Maximum Peak resonance specifications (MPRS) technique. Pre determined phase margin and bandwidth ensures the system stability. Khodabakhshian [75,76] modified this technique and applied it for first time in power systems. The author also designed a new PID load frequency controller for a single machine infinite bus hydro system as well as for automatic generation control of hydro power plant in multi machine system. Stability and dynamic of this controller has shown enhanced damping of power system and better performance over conventional PI controller.

5.2. Alternative control methods

Apart from conventional control methods, some authors have proposed different alternative control methods to stabilize the frequency variation. One way to control frequency variation is to employ ballast/dump load as proposed in Ref. [5]. Operation of dump load can be controlled with the Electronic Load Governor (ELG). ELG consists of an electronic device that controls frequency by automatically varying the ratio of actual load and dump load so that load on generator remains constant. Henderson [77] applied ELG for micro hydro power plant ranging from 1 kW to 5 kW which provides electricity to remote regions. The ballast/dump load concept is illustrated in Fig. 8.

Dump load assures frequency control however, it dissipates a large amount of generated power due to variation in the load. Efforts have been made to reduce the amount of dissipated power as much as possible in dump load. Doolla and Bhatti [78] proposes a new cost-effective technique for load frequency control by reducing the size of dump load. Input power can be controlled by ON/OFF controlled valves. The paper tested two control techniques consisting of two pipe control and three pipe control mechanism. Two pipe control method resulted in 50% reduction in the dump load and three pipe control method resulted in 30% reduction in dump load size saving of precious energy from dissipating. The controllers costs including valves was still less than the cost of dump load. Doolla and Bhatti [79] applied the same technique for automatic generation control of mini hydro plants operating in isolated mode for fully eliminating dump load, though the settling time was very large around 200 s.

5.3. Intelligent control methods

Conventional PID controllers suffer from limitation of tuning parameters for giving optimum control of frequency. Many researchers have implemented intelligent control techniques including Fuzzy logic control, Neuro-fuzzy and artificial neural networks for optimum control of frequency operating in isolated and remote regions. Salhi et al. [80–82] implemented fuzzy logic control for load frequency control in micro hydro power plant based on the Mamdani inference system and Tekagi-Sugeno inference system. In this paper, two fuzzy sets are performed. The first set is fuzzy controller which maintains frequency variations and regulates waste of available water on reservoir. The second set is fuzzy supervisor which controls electrical production between departures because the mini grid is divided into three sub-networks (departures) that are powered by the order of preference. This method provides cost effective solution for providing electricity to those near to mountains [80–82].

Fuzzy logic can also be applied for parameter tuning of conventional PI controllers for its optimum operation in isolated mode. Conventional PI controller has disadvantage of their parameter tuning because these values cannot be changed automatically according to load. Fuzzy controller is designed for providing self tuning of PI controller in mini hydro power plant operating in isolated mode where load is continuously changing [83]. Ozbay and Gencoglu [84] presented novel technique based on adaptive fuzzy control for frequency control of mini hydro plant. It compares both linear and nonlinear turbine model neglecting the surge tank effects and inelastic water column. This paper implemented an adaptive fuzzy controller as regulator for regulating frequency within its range. Çam [85] compared PI controller with Fuzzy gain scheduled PI controller (FGPI) for frequency control of hydro power system in single and two area plants. Simulations results showed that FGPI is considerably advantageous in reducing overshoot, undershoot and settling time than PI controller. Settling time varies directly to generated power in power system. Hence, reduction in settling time significantly reduces generating cost of the electrical energy. This contributes to the economy both to management as well as to consumer. Corrosion can be avoided by obtaining lower overshoot within system resulting in longer life cycle of plants [85].

Control for water flow is very necessary for number of applications as in hydro power, tank water etc. Turbine gate opening and water flow plays an important role for more generation and in maintaining the system frequency. At present, water is controlled by conventional techniques. However, they can be controlled robustly with Fuzzy logic control. Niimura and Yokoyama [86] implemented fuzzy logic for water level control and provided a comparison with a conventional controller through simulation. It has proved that implementation of fuzzy logic control for water flow control increased power generation which is not optimally obtained due to wastage of water because of delay in water control. It was observed that with manual control for 30 min intervals produces 820 kWh and fuzzy provides 882 kWh of energy.

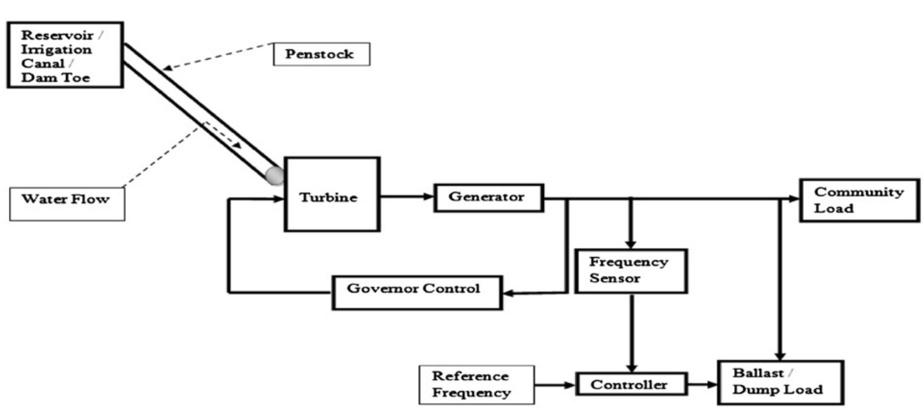

Fig. 8. Schematic diagram of mini hydro power plant with dump load.

In Refs. [87,88] water flow control approach to control hydro turbines speed as well as power has been employed. Single gate control technique was employed in Ref. [88] whereas Ref. [87] implemented three gate control for water regulation. Both paper applied spear valve to control rotary motion by which mini hydro plant power can be controlled. Servomotor controls rotary motion of spear valve. An advanced controller is presented in Refs. [89,90] consists of four control schemes for dividing control action into nonlinear and linear parts which shows best response over other controllers. The implementation of this technique on mini hydro power plant yields approximately same results as from simulation. The linear part is formed by adaptive fast transversal filter (FTF) algorithm and Normalized least mean square (LMS) algorithm. Fuzzy PI and Neural Network form nonlinear part. The proposed technique is compared with six other techniques and resulted in lowest undershoot (0.69), overshoot (0.2798) and smaller settling time to all other techniques. Table 5 shows the summary of all governor control techniques for frequency control.

6. Technical and economical analysis

The total cost of mini hydro power plant consists of four main parts as shown in Fig. 9. The most expensive part is the construction part which takes up to 40% of the total system cost followed by electrical and mechanical equipments cost (turbine generator set) which is 30% of the project cost. The control equipments and management cost consists of 22% and 8% respectively [91]. The total cost of mini/micro hydro schemes varies from $1500 to $2500 per kilowatt of installed capacity [5,13,92].

Roque et al. [93] presented the economical analysis of 400 kW micro hydro power plants. The economic analysis of MHPP has shown that it involved total cost of 393 K euro with a pay-back period in six years. Besides economy of these MHPP, this generation will help in regulation of water courses [93]. Ghadimi et al. [94] presented the economical analysis of two sites in Iran. The economic cost includes all the cost and expenses associated with power plant construction, installation, and equipment. The total cost for micro hydro power plant is $670 per kilowatt with pay-back period in less than one year. The minimum and maximum pay-back periods of different renewable energy resources is shown in Fig. 10 [95], which shows that micro hydro plant has the lowest minimum pay-back period than other resources.

Maher et al. [96] discussed different rural electrification options operating off-grid suitable for low-income households of Kenya and compared Pico hydro with solar home systems. He concluded that the Pico hydro is presently more cost effective than solar home system having 15% less cost per kWh than the cheapest solar home system. Nouni et al. [97] discussed with economy of different micro hydro schemes implemented in remote regions of India. It was also suggested that government should offer subsidies for development of mini hydro projects in order to reduce the unit cost of electricity [97].

Li et al. [98] discussed the economical analysis and calculation of micro hydro potential for future installation in different canals of the Chia-Nan Irrigation Association of Taiwan having head more than 2 m. It was observed that water head contributed more to payback period than water flow rate. It was recommended that an irrigation canal having higher water head is more economical than with higher water flow rate.

6.1. Cost calculation of hydro system through RETScreen software

The RETScreen software is the product of Natural Resources Department of Canada. It is a free software for determining the

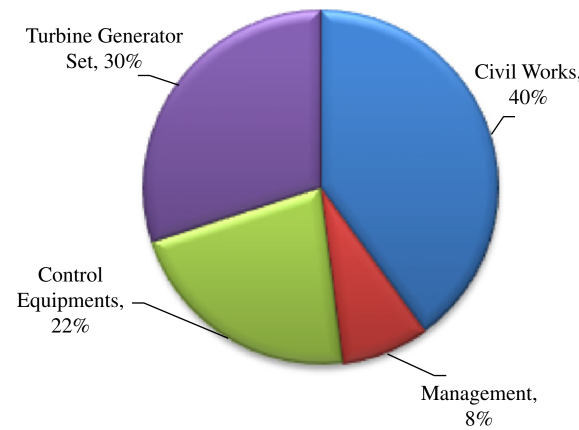

Fig. 9. Cost division of mini hydro project [91].

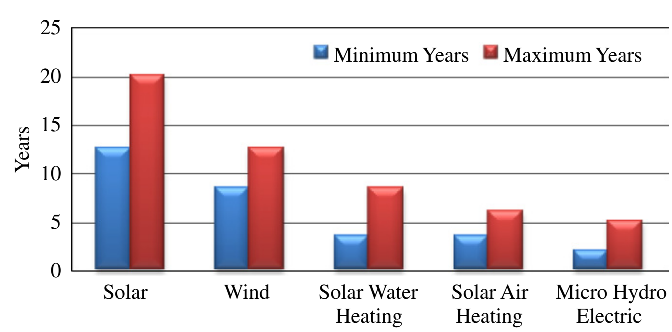

Fig. 10. Payback period of renewable energy resources [95].

Table 5
Summary of all governor control techniques.

Governor type	Controllers employed	Main theme of techniques
Conventional governor control.	These governor employed mechanical hydraulic governor, PID and PI controller.	These controllers provide frequency control by tuning parameters of PI and PID controller for frequency regulation [69–73].
	Optimization of PID parameters is also carried out for better results	Parameter optimization provides improved results [74–76].
Alternative control	These control methods employed ballast load concept for frequency control	Ballast load provides good frequency regulation when operated off-grid, but wastes large amount of energy [77].
		Techniques have applied to reduce dump load capacity in order to save energy [78,79].
Intelligent control	This control method involves application of ANN and fuzzy techniques for improvement of PID controller or directly applied fuzzy logic control and ANN for frequency control.	Fuzzy logic and ANN techniques can be applied for parameter optimization of PID and PI controllers [83–85].
		Fuzzy logic control provides robust frequency control of mini hydro power plant [80–82,86–90].

feasibility, technical viability of renewable energy projects such as Solar, wind, geothermal and hydropower. This software deals in 36 world languages [99]. RETScreen software is used by various researchers to find the total estimated cost of solar power plants [100,101] and solar water heating system [102]. The usage of RETScreen for total cost of mini hydro system is carried out in Refs. [92,103]. By applying the details of parameters like power potential, head, water flow, number of frost days at site, turbine type, road construction length, penstock length, transmission line length, grid connection type and voltage, the software provides the number of factors like turbine runner diameter, penstock thickness and hydraulic efficiency losses and in the end, the total construction cost estimates will be produced [92]. Furthermore, the worldwide meteorological data has been incorporated directly into the RETScreen software, which help to overcome the costs and difficulties associated with gathering meteorological data, and product performance data [103].

6.2. Cost calculation of electro mechanical components

The cost of electro–mechanical equipment is very important in mini hydro development because it includes more than 40% of total plant budget and plays a very vital role in the feasibility of project. In order to calculate the cost for total mini hydro power plant, a number of equations are provided [15,91] based on power and total head. These equations provides the cost by considering the Pelton wheel, Francis, Kaplan and semi Kaplan turbines having range below 2 MW. The most common equation for calculating cost is given by [15,91]

$$\text{Cost} = a \times P^{b-1} \times H^{c}\,(\text{€}/\text{kW}) \tag{4}$$

where, coefficients a, b and c depends on the geographical and time field in which they are used, P and H represents power and net head of mini hydro power plant.

Aggidis et al. [104] developed empirical formula for cost estimation of the electro–mechanical equipment and different turbines. The developed empirical formulae help in a quick estimation of the minimum costs for the electromechanical equipments that may be used for energy production. Aslan et al. [105] discussed the economical cost of a mini hydro power plant with optimum efficiency by analyzing seven different location with three turbines (Cross flow, Francis and semi-Kaplan) for its implementation in Kayabogazi dam.

6.3. Discussions and recommendation

The potential of mini/micro-hydro plants have not been fully utilized for energy generation due to their high capital cost. This high cost is mainly due to the cost of equipment. In order to cope with the rapid increase in energy demand, reduced costs of these plants is necessary. One way of reducing this cost is the replacement of conventional equipments with economical alternative equipments like PAT and induction generator.

Another way of making these schemes practical is to motivate Private companies and banks to participate in these micro hydro schemes. Private companies can be motivated to participate in micro hydro schemes for rural electrification, even in a poor country through a suitable legal framework and options of risk management. Pigaht and van der Plas [106] presented the role of the private sector in development of micro hydro project in Rwanda. With private sector participation (PSP) role, four Rwandan companies have been registered and each is constructing a 100–500 kW micro-hydro plant. The finance of each of the plants was carried out by the companies' own equity and debt including 30–50% subsidy from PSP hydro project. With the support and role of the PSP hydro project, approval of micro hydro schemes was granted in 2–12 weeks. Because of PSP efforts, 5 private companies have been registered whereas before this there was not even a single private company expert in micro hydro schemes in Rwanda.

From these experiences, it was concluded that local participation at every stage plays an important role for sustainable rural electrification development through micro-hydro schemes. Without their contribution, experiences all over the Africa and Central Asia have shown that these schemes suffered large dependence on foreign consultants. Micro- hydro schemes were transferred fully to local community for operation after installation, which resulted in failure of these schemes because, maintenance and operation was normally beyond the capacity of local villagers [106].

For making mini/micro hydro power plant a cost-effective option and technically economical, following recommendations are proposed:

(1) license to private companies should be approved within minimum time to make these schemes successful as shown by PSP hydro project Rwanda providing approval of electricity projects within 2–12 weeks [1,106].
(2) Variable speed turbines can be used through power electronics applications to generate constant 50 Hz. This allows for using simple propeller turbines instead of Kaplan turbine [1].
(3) Pump as turbine (PAT) can be a most economical option for micro/Pico hydro and even for mini hydro schemes in some cases [31,32].
(4) Induction generators can replace synchronous generator resulting in total reduction of mini hydro schemes [40–42].
(5) With the implementation of new intelligent controllers for water control as well as frequency and active power control, these schemes can be successfully operated with good efficiency.
(6) Guide vanes and adoption of electronic load controllers should be eliminated to reduce the cost [16]. However, if it is necessary then the energy wasted in dump load should be used for other purpose such as garden lighting, charging of battery, water heating, cooking and space heating.
(7) Main issue is to disseminate technology at commercial level so that these cost effective options can be best adopted. According to a report presented by Global Network on Energy for sustainable development there is lack of awareness, lack of financial mechanisms and lack of technical expertise. Recent developments are made in Kenya and Nepal regarding the Pico hydro turbine. These countries should produce these Pico hydro turbines at commercial level and also disseminate this throughout the world because these are cost-effective and highly efficient [25].
(8) Motivation to Private Support Participation must be carried out through media and through the provision of certificates to many parties with proper incentives and subsidies for 5 years or more. Special subsidy and liberal term load should be allocated for exploring micro hydro plants for developing the interest of private companies [16,106].
(9) Local resources of equipments and maintenance by experts should be employed to reduce the cost of plant.
(10) By employing new emerging designs in civil works, cost of civil construction can be reduced. By efficiently utilizing the civil construction already available at rivers and by minimizing the dimensions of the power house, control panels, panels for instrumentation and protection can be accommodated in mezzanine floor to minimize the span of power house. Construction cost can be further reduced by using sandy soil and masonry techniques [1,3,16].

(11) To ensure that micro hydro projects survive, the government or private companies should provide proper training to locals people of that region and if necessary involve them during installation and develop a sense of ownership [2–4,27].
(12) Government should introduce supporting programs for encouraging local manufacturer, site survey, scheme design and installation should be done by local experts [96].

7. Conclusion

Mini hydro schemes can be adapted as the most economical option for rural electrification than any other available renewable energy sources such as solar and wind. New designs in propeller turbine and alternative option such as PAT, induction generator and intelligent controllers can successfully make these schemes more economical and cost-effective options. However, the successful operation of these schemes greatly depends upon government efforts and subsidy initiatives. Private sector participation should also be encouraged through a combination of bank loans and government incentives. It is expected that implementation of mini hydro schemes with new cost-effective designs will result in growth of local industries, which will lead to overall economical and social development in developing countries.

Acknowledgments

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